

# Scanning Electron Microscopy in Failure Analysis and Accident Investigations

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## ABSTRACT

*Fractography is a science of studying fracture surface characteristics. When engineering structure/component fails it leaves certain signatures on its surface. The study of these signatures with the help of Scanning Electron Microscope (SEM) provides valuable information to (a) understand the failure process i.e. crack initiation and propagation directions (b) existence of loading conditions at the time of failure (c) underpin the causes of failure etc. In this paper, a few failure cases viz., failure of LPTR blade of aero engine, failure of engine of an aircraft, failure of roller shaft and input shaft of power steering, failure of bevel gear and pinion of engine gearbox were presented. The failure case studies amply show that fractographic study is inevitable for conducting successful failure analysis and accident investigation. Further, a typical fractographic features observed in CFRP composite laminates failed under different loading conditions were presented. This fractographic data obtained from laboratory control specimens extends SEM role in the analysis of composite material failures.*

**Keywords:** Scanning Electron Microscope, Failure Analysis, Composites, Fatigue, Fracture.

## 1. INTRODUCTION

Failures in engineering structures/components and not paying attention to analyse the reasons for failure are commonly observed. Replacing the defected component without analysing the reasons for failure and continuing with the existing problem is quite dangerous. The failure leading to catastrophic failure and some time causes even loss of human life. To prevent failures, failure analysis is inevitable. Although failure analysis requires many considerations, fractographic study with the help of SEM plays a major role in identifying the failure mode and hence cause of failure. On the other hand, composite materials are being widely used in variety of applications, due to their high specific strength, specific stiffness etc. The use of advanced composite materials in aerospace industry has gone up to 50% in civil aircraft and more than 80% by weight in defence aircrafts. The increasing use of composites in aerospace industry, the number of failures may increase and need more attention to understand failure mechanisms in these materials. Unlike metals, polymer composites undergo

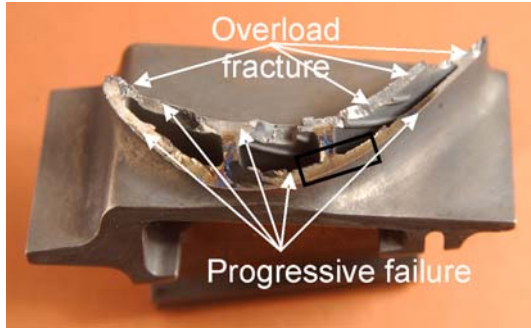
highly complex three dimensional damage failures under different loading conditions. Study of these composites failures will help the designers, manufacturers and users to prevent failures. The purpose of this paper is to present few case histories that were investigated at our laboratory during recent past emphasizing the need for SEM in failure analysis and accident investigations and to present few fractographic features observed in CFRP composite laminates failed under different loading conditions.

## 2. CASE STUDIES

### 2.1 Failure Analysis of LPTR Blades of an Aero Engine

The failure occurred during test run of the engine and resulted in damaging various components of the engine. The fractured blades were examined under stereo binocular microscope (Fig. 1) and SEM for identifying the fracture features. The fractography showed that the blade had failed by fatigue (Fig. 2a and

Fig. 2b). The fatigue cracks initiated on the convex surface of the airfoil propagated progressively over about 80% of the blade cross-section and finally failed by over load fracture.



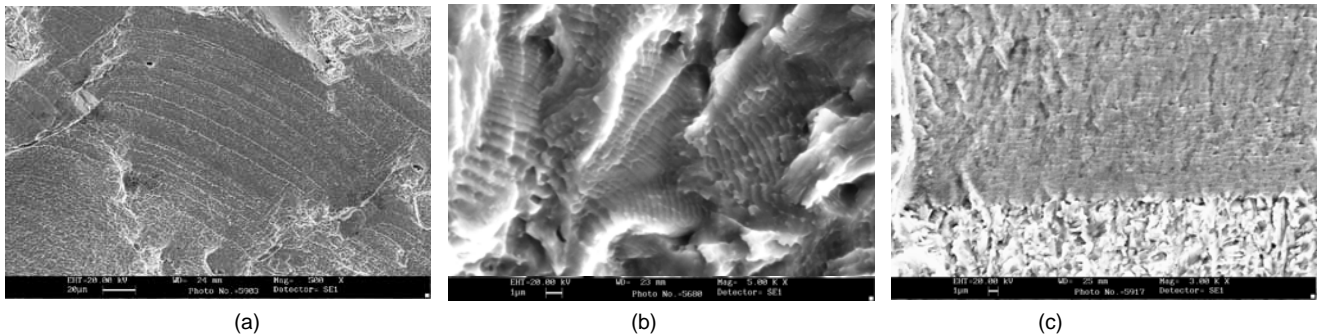
**Fig. 1:** Fracture Surface of the LPTR Blade of Aero Engine

Examination revealed that the fatigue cracks had initiated in platinum aluminide coating on the blade aerofoil (Fig. 2c). Number of cracks was found in the coating surface and one of these cracks had subsequently propagated by fatigue leading to the fracture of the blade. Analysis revealed that the blade undergone

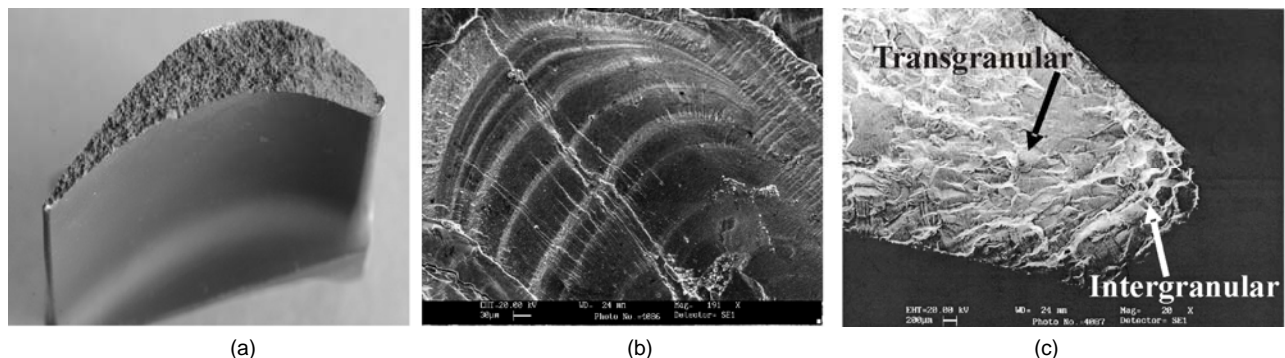
excessive bending which has resulted in generation of fatigue cracks on the airfoil surface close to the root.

## 2.2 Failure of Engine of an Aircraft

Aircraft met with an accident during flying. After detailed investigation of LPTR blades, HPTR blades, Low-pressure nozzle guide vanes, high pressure nozzle guide vanes and portion of hydraulic reservoir parts, one of the LPTR blades (Fig. 3a) had failed by fatigue and all other blades and vanes failed by over load. Fractography revealed that, the fracture had initiated at the leading edge and showed the presence of faceted fracture features. SEM fractographs showed well-defined beach marks typical of fatigue (Fig. 3b). Higher magnification images clearly revealed that the crack had initiated initially by intergranular and later propagated by fatigue (Fig. 3c). The reason for intergranular crack propagation is due to high operating temperature and high stresses on blade surface. Hence stress rupture has taken place at the leading edge and later propagated by fatigue before culminating in over load failure.



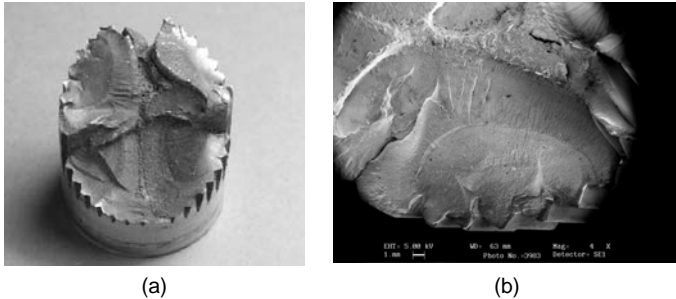
**Fig. 2:** SEM Fractograph of (a) Crack Arrest Marks Typical of Progressive Failure, (b) Fatigue Striations, (c) Fatigue Striations Parallel to the Coating-Blade Material Interface



**Fig. 3:** (a) Fracture Surface of Failed Blade, (b) Crack Arrest Marks Typical of Progressive Failure, (c) Intergranular and Transgranular Fracture Features

### 2.3 Failure of Roller Shaft and Input Shaft of Power Steering

The investigation team received two service failed components namely a rotor shaft and an input shaft of power steering gears. The shaft had fractured in the splined root region in a spiral fashion. Examination revealed that four fatigue cracks (Fig. 4a) initiated on the shaft at approximately 90 degree to each other and propagated simultaneously over about 90% of the cross section before giving way to final over load fracture.

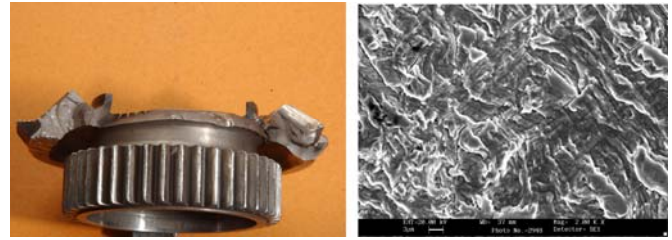


**Fig. 4:** (a) Fracture Surface Showing Multiple Crack Origin, (b) Beach Marks Typical of Fatigue Failure

Figure 4b shows beach marks typical of fatigue originated at the spline root region propagated towards the centre of the shaft. The fatigue appears to be a high cycle—low stress type. The reason for fatigue crack initiation at the spline root region is due to less root radius. The negligible root radius might have given rise to stress concentration which facilitated to initiate fatigue crack. No metallurgical abnormality was responsible for the fatigue initiation.

### 2.4 Failure of Bevel Gear and Pinion of Engine Gear Box

The failure occurred during endurance testing of an engine. As per the report the failed gear box is a modified one. The bevel gear and spur gear were joined together by electron beam welding to form an integral part (Fig. 5a). Detailed examination revealed that, the fatigue crack (Fig. 5b) initiated at the weld joint and propagated across the bevel gear. Cracks were also observed at the spline root regions. Change in microstructure and hardness variation in the weld, bevel gear and spur gear assembly clearly indicates the residual stress concentration was very high at the weld region. This has caused to initiate fatigue crack at the weld region.



**Fig. 5:** (a) Photograph Showing Failed Component, (b) Fatigue Striations

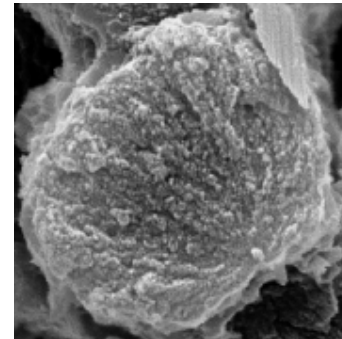
## 3. IDENTIFICATION OF FRACTURE MODES IN ADVANCED CFRP POLYMER COMPOSITES

Identification of fracture features in polymer composites is quite complex and repeatability of these fracture features through simulated studies is sometime not possible because of its complexity in fabrication and processing conditions. Some laboratory tests were carried out on both CFRP prepreg laminates and CFRP Resin infusion technology. Common fractographic fracture features recorded on failed composites when they were subjected to loading conditions like tension, compression, flexural, impact and fatigue tests. These fracture features have been used for analysing the failure mechanisms in composites.

### 3.1 Tension

#### 3.1.1 Fibre-Dominated Fractures

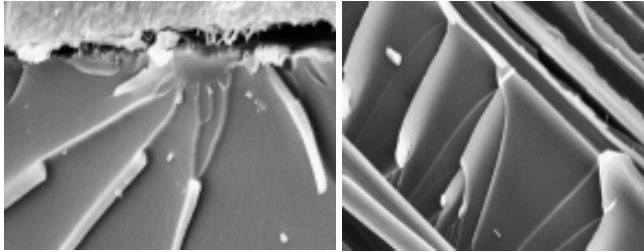
Macroscopically, existence of discrete fibers (or bundles of fibers) pulled from the surrounding matrix is indicative of failure in tension. One of the microscopic features indicative of tensile type failure is the characteristic known as fibre radials. The failure origins can be traced using the fibre radials.



**Fig. 6:** Fiber Radials Observed in Tension Failure of Fibers

### 3.1.2 Resin-Dominated Fractures

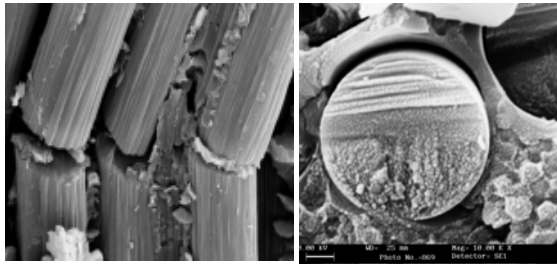
Two features characteristic of matrix tensile fracture: river markings (Fig. 7a) and hackles (Fig. 7b). Hackles are numerous platelets of fractured epoxy distributed in rows between fibers. Hackles have been observed under a variety of failure conditions including interlaminar and intralaminar delaminations, as well as pulled-out fibers under tension.



**Fig. 7:** (a) River Pattern;  
(b) Hackles Observed in Tension Failure of Matrix

### 3.2 Compression Failure

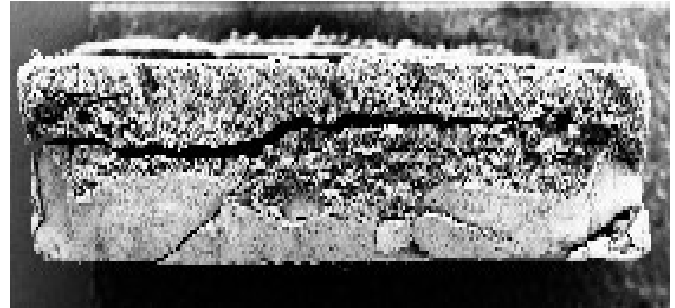
The macroscopic appearance of the fracture surface will be relatively smooth and will be oriented at an angle of 30–45° to loading direction. Fiber kinking (Fig. 8a) is a characteristic of compression failure. At high magnifications, the fracture surface of the individual fibers showed two distinct areas of compressive and tensile areas separated by neutral axis known as chop marks (Fig. 8b).



**Fig. 8:** (a) Fiber Kinking, (b) Tension and Compression Regions Separated by Neutral Axis (N.A)

### 3.3 Flexure Failure

Flexural failure in unidirectional laminates shows areas of tensile fracture and compressive fracture, the boundary between them being parallel and often close to the neutral axis of the laminate on the individual fibre ends (Fig. 9). Flexure produces an overall fracture topography somewhat similar to that noted for individual compressive fibre fractures.



**Fig. 9:** Fracture Surface Showing Rough Surface on Tensile Side and Smooth Surface on Bottom Compression Side

The tensile and compressive loads applied during flexure generate relatively large-scale areas of compressive and tensile fiber fracture, separated by a distinct neutral axis line. The position of the neutral axis may be of value in reconstructing the loading conditions of flexure at the time of failure.

## 4. CONCLUSIONS

Failures in engineering structures/components are frequently occurring due to various reasons. To minimize the occurrence of such failures, failure analysis has to be conducted. This will help the manufacturers, designers and operators to prevent future accidents and failures. To achieve this, fractographic analysis of failed components with help of SEM is not only necessary but also essential in failure analysis and accident investigations.